Neutral Beam heating progress on LTX-β

W. Capecchi, J. Anderson, UW Madison
S. Banerjee, R. Bell, D. Boyle, A. Maan, R. Majeski, PPPL
D. Elliott, ORNL

Neutral beam important for studies on LTX-β

- LTX- β provides testbed for study of energetic particles (EPs) in low-recycling boundary plasmas
- Fueling essential for plasma sustainment during low-recycling phase (no gas puffing)

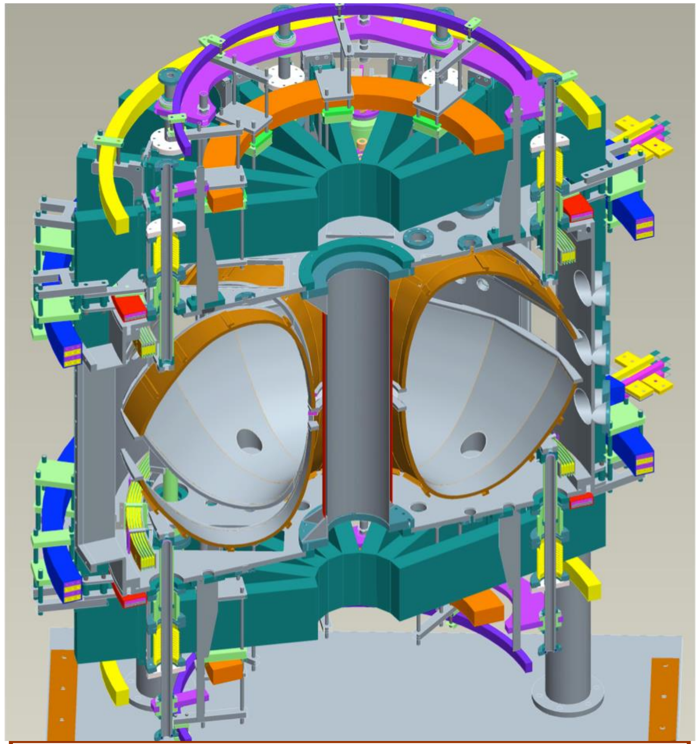
  [Elliott D. et al 2020 IEEE Trans. Plasma Sci. 48 1382–7]

- Auxiliary heating probes energy scaling in low-recycling plasmas previously observed to exceed ITER98P(y, 1) ELMy H-mode scaling by factor of 3

  [Kaita R. et al 2007 Phys. Plasmas 14 056111]

- Lithium coated first wall via evaporation led to observation of flat T_e profiles

  [D Boyle et al., *PRL* **119**, 015001 (2017)]



Lithium Tokamak Experiment Beta

R=0.4 m; a=0.25 m

I_p ~ 100 – 150(?) kA

|B| ~ 0.3 T

$T_e(0)$ ~ 200-300 eV

n_e ~ 5×10^{13} cm^{-3}

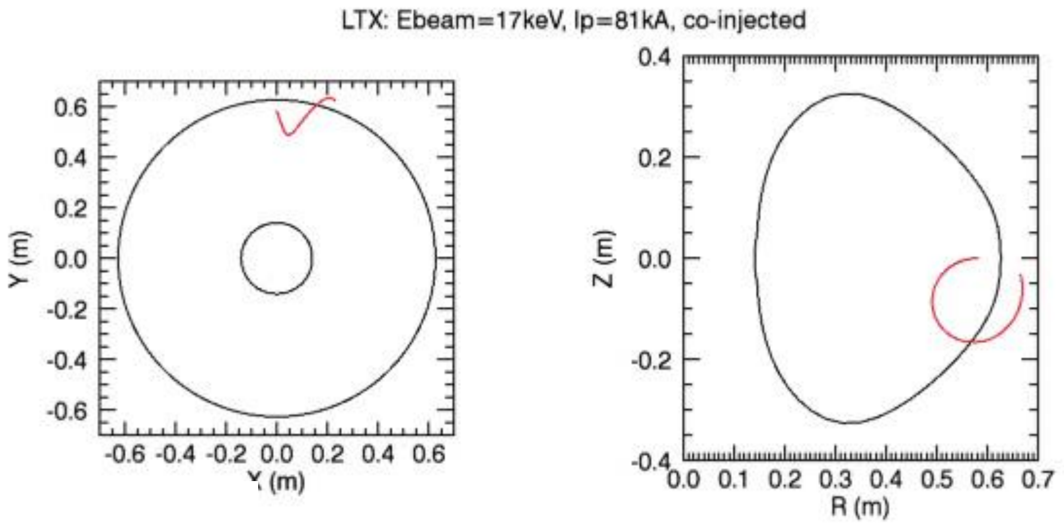
Pulse length ~ 50 ms

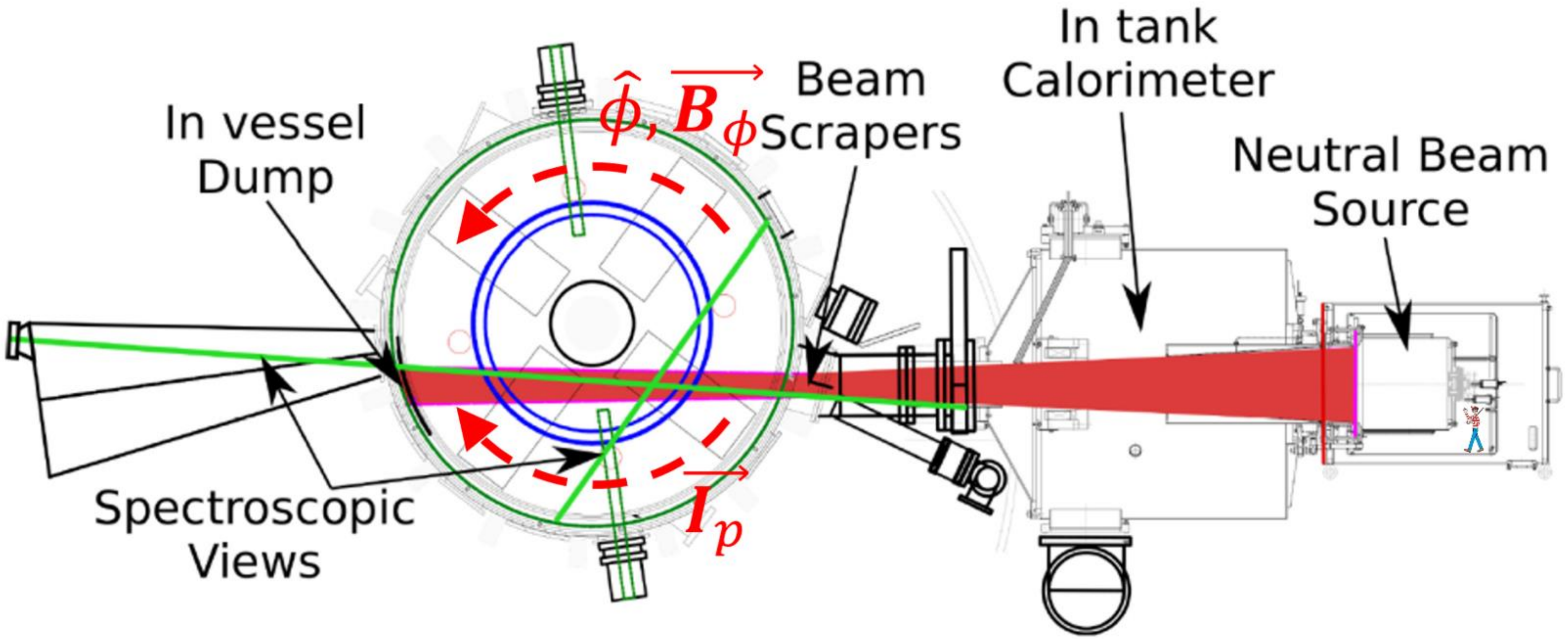
Outline

- Prompt loss in low current plasmas & Modeling of beam coupling dependencies
- Experiments at higher current (good confinement) plasmas
  - No evidence of beam heating/deposition
- Beam improvements/optimization
  - New gas valves, realignment, fueling optimization, performance checks
- Evidence of beam in plasma signals
  - Fast ion physics, density threshold

(near) total prompt loss in < 100 kA plasmas

- NBI installed 2019, plasmas limited to < 100 kA
- Ions drift vertically to impact vessel boundary typically within first poloidal transit
- Loss drives counter-NBI torque
[Hughes P.E. et al 2021 PPCF (2021)]

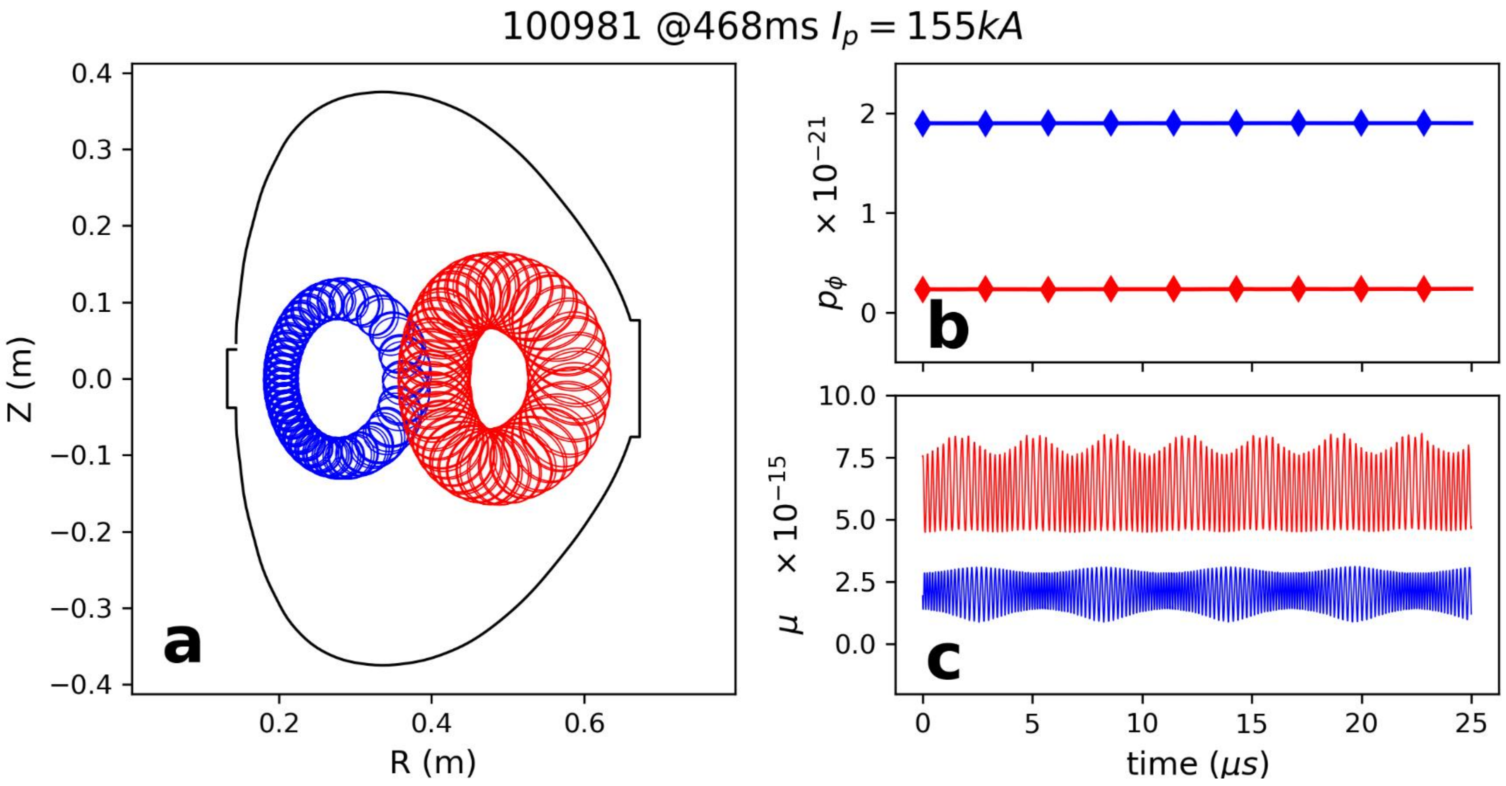




NBI Parameter	Specification
Beam energy	20 keV
Beam power	700 kW
Pulse length	5-7 ms
Composition	100% H

Modeling shows good coupling possible in LTX-β

- TRANSP/NUBEAM, CONBEAM (orbit topologies), and **POET** (3d orbits) give comprehensive understanding of beam parameter space
  - Good confined passing orbits (non-adiabatic effects small)
  - Low- vs high-field side coupling
  - Parameter dependence



Well confined orbits for co- (red) and counter-injected (blue) beam ions

[W. Capecchi *et al* 2021 *Nucl. Fusion* **61** 126014]

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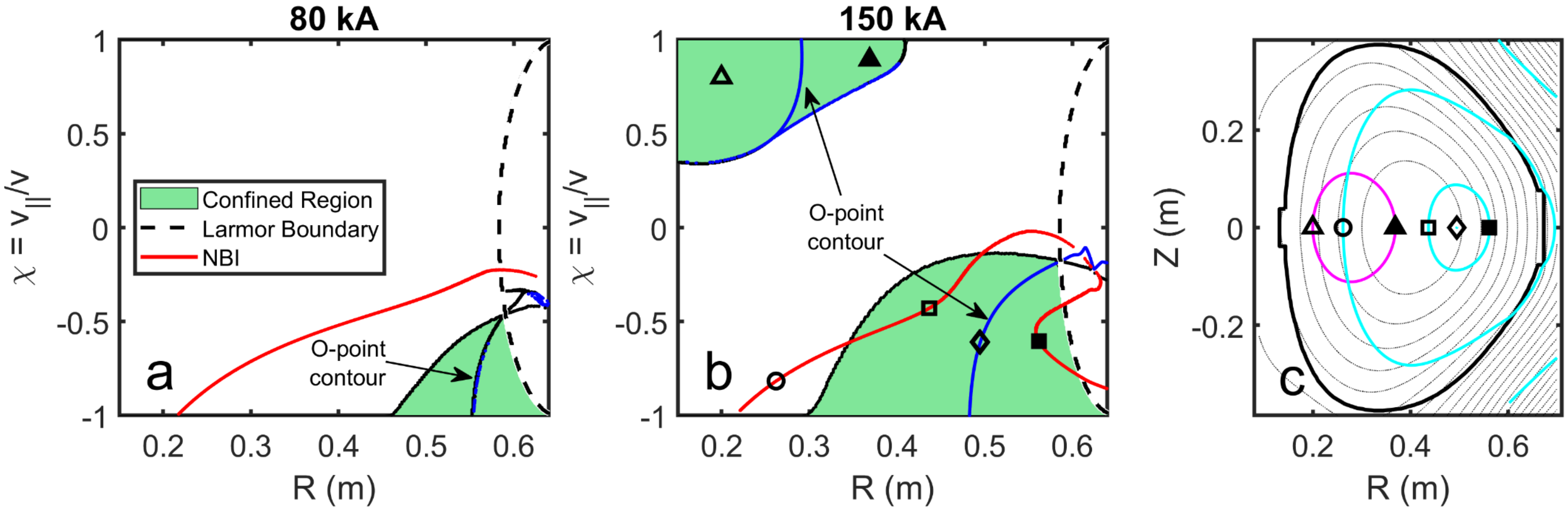

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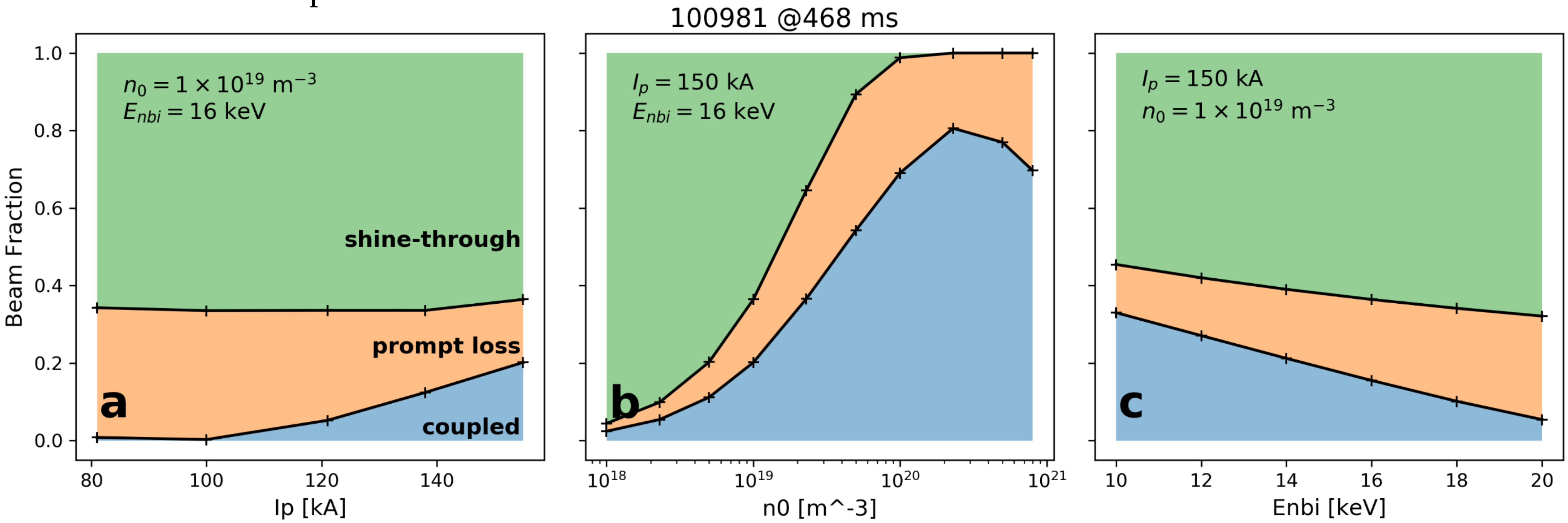

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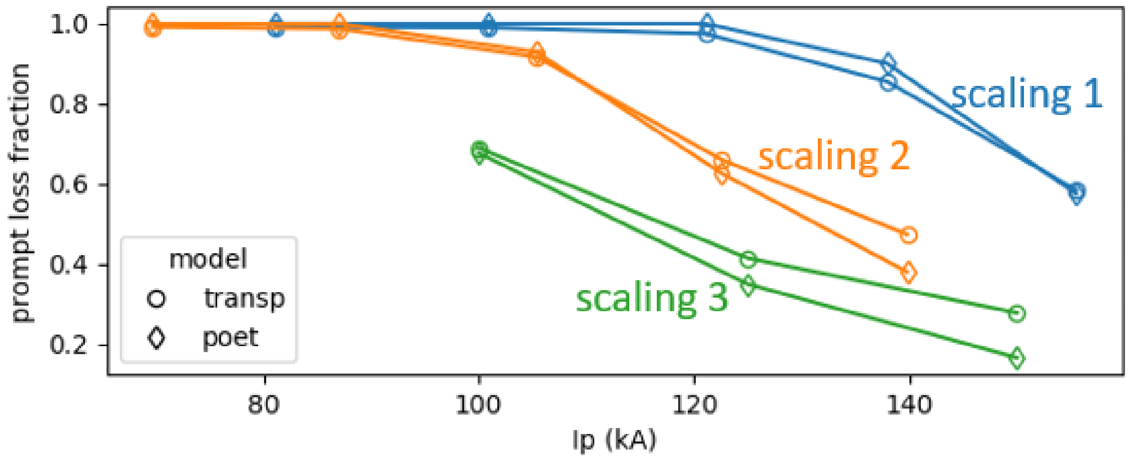
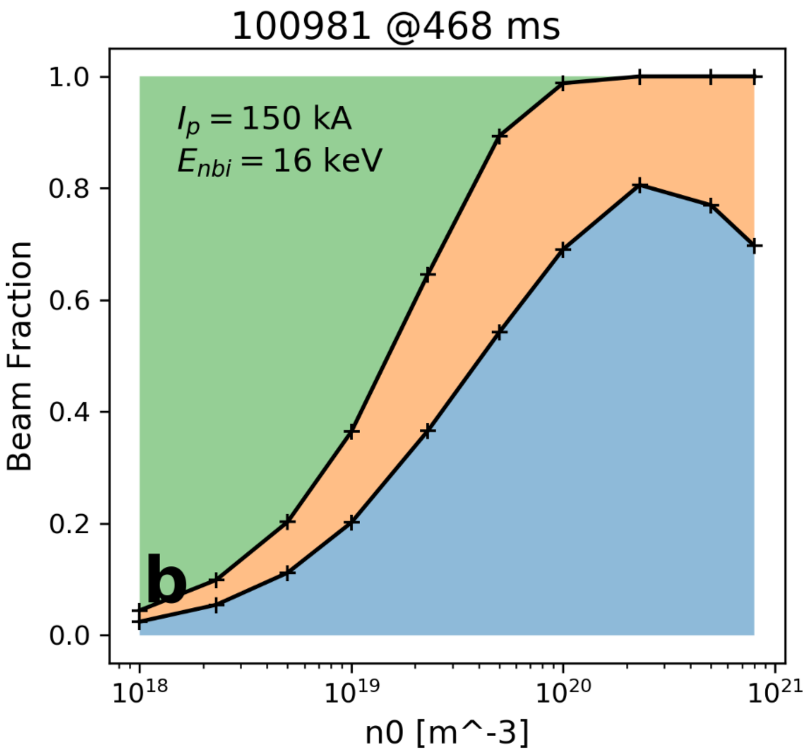
Good coupling >100kA, >1e19m^-3

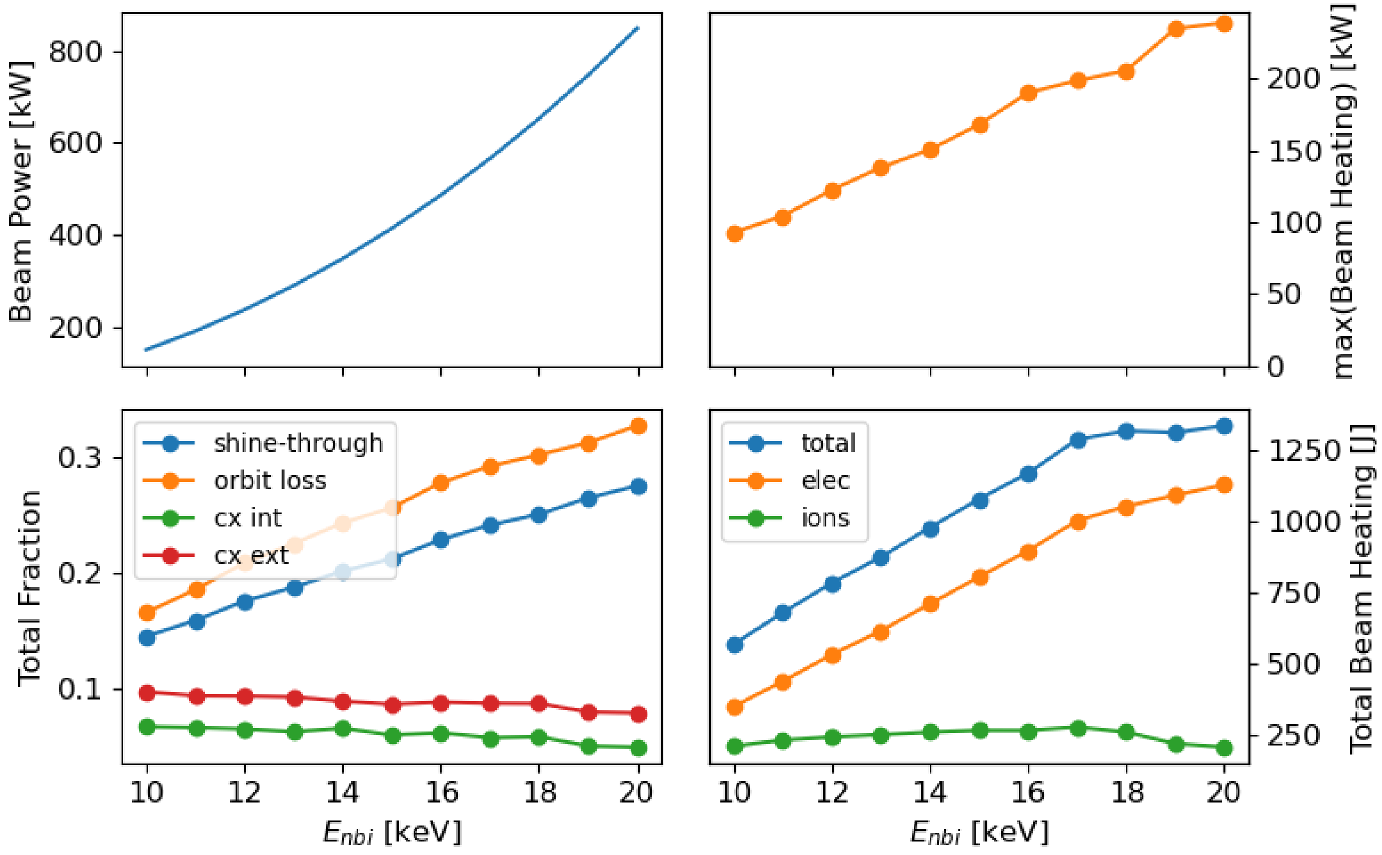




[W. Capecchi *et al* 2021 *Nucl. Fusion* **61** 126014]

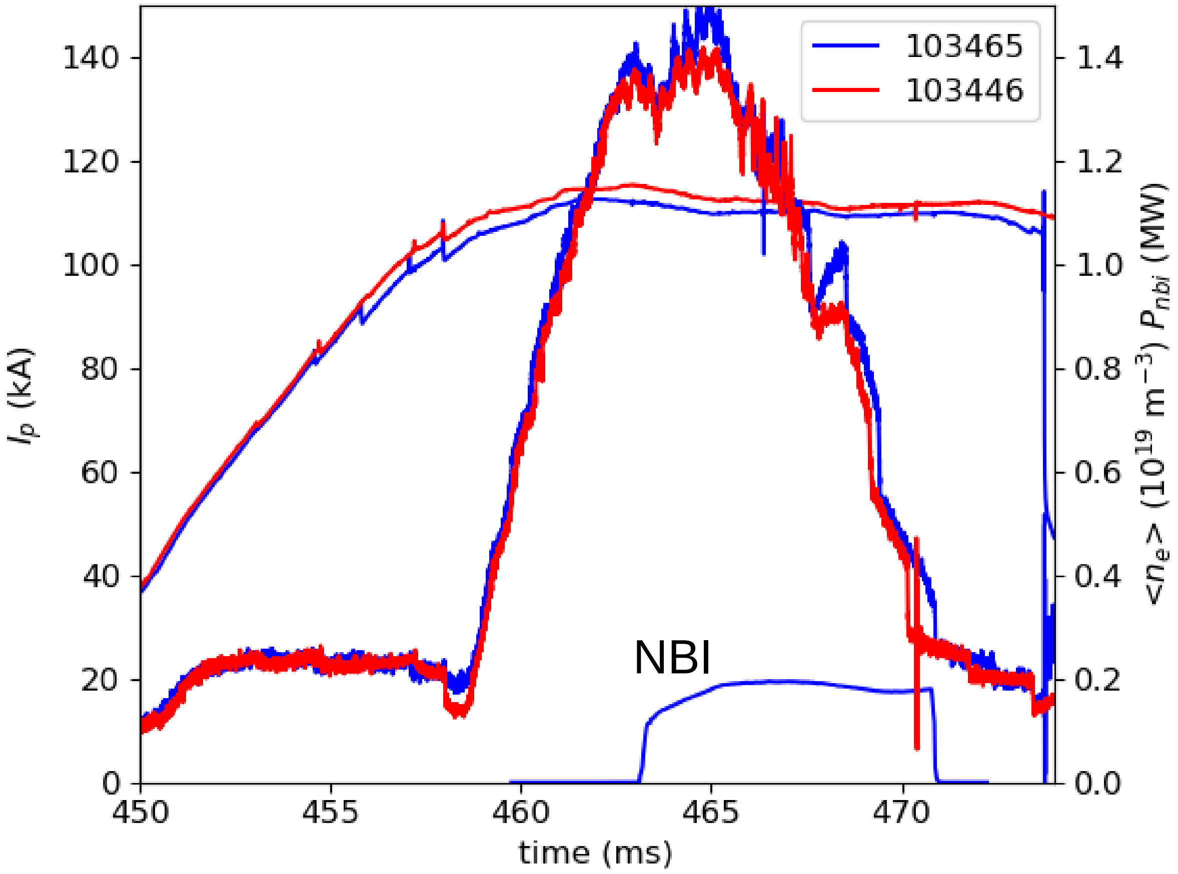
Initially no evidence of beam in plasma

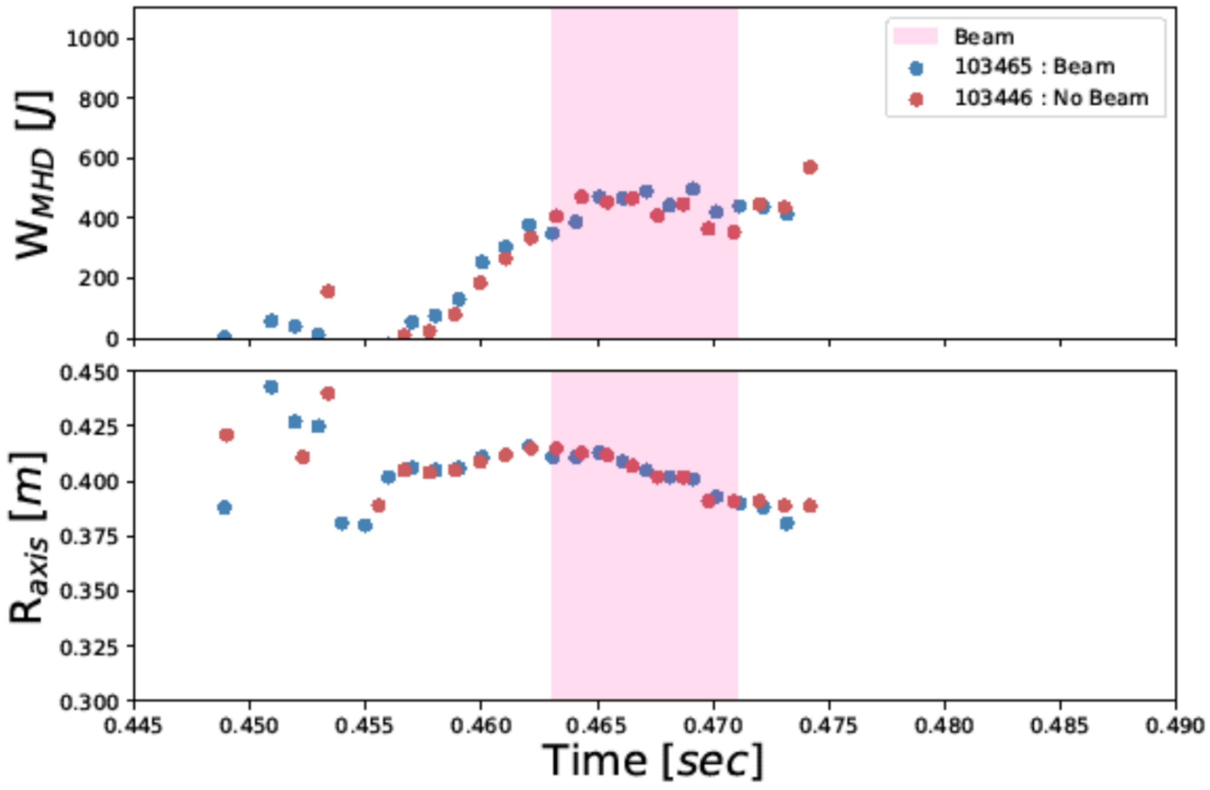
- ~July 2021 achieved 125 kA plasmas
- Sought beam heating in high density discharges
- Tried both low beam energy (good coupling) and high (worse coupling, higher power)



Initially no evidence of beam in plasma

- ~July 2021 achieved 125 kA plasmas
- Sought beam heating in high density discharges
- No change observed in density, Thomson, stored energy, etc





(credit Anurag Maan)

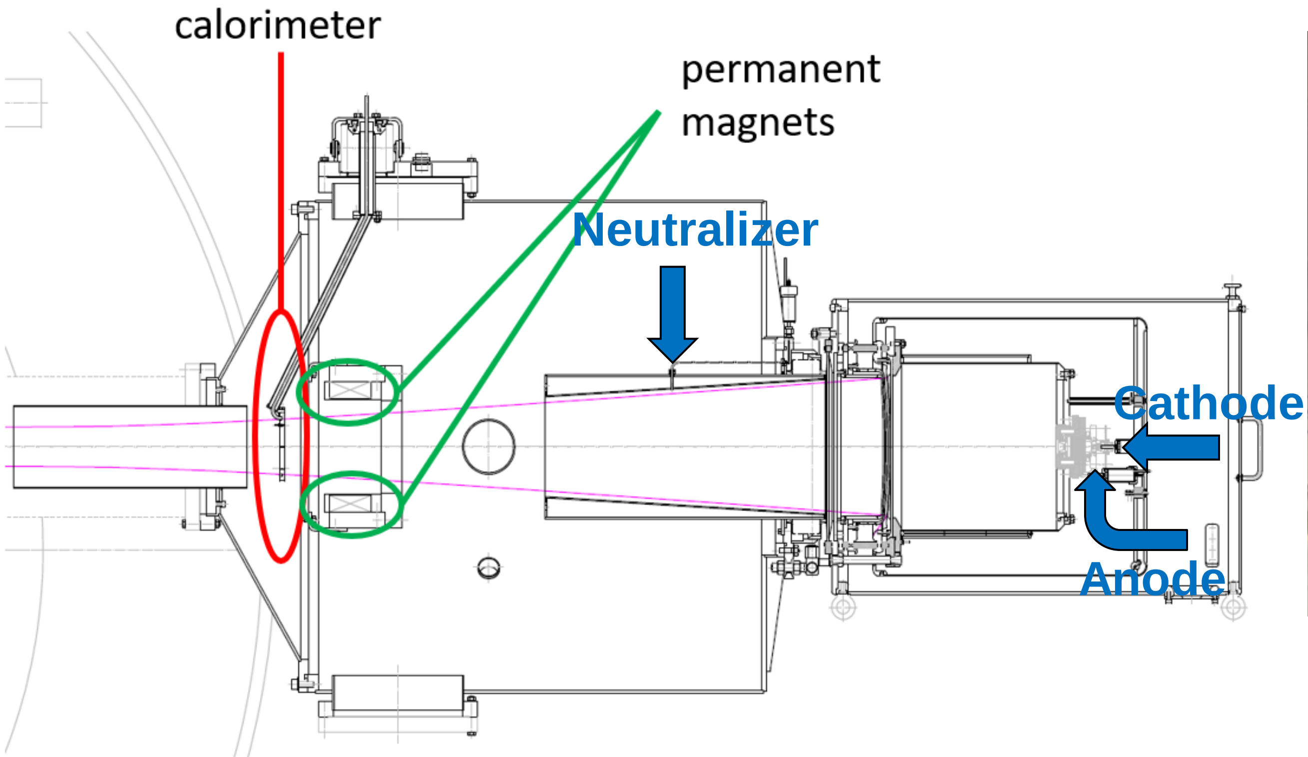
What’s happening to the beam?

- What’s happening to the beam before it enters vessel?

  Investigation into beam performance led to improvements:

  - Improved gas dynamics in source/neutralizer with new valves/orifices
  - Visual inspection of grid/source
  - Neutralization optimized
  - Beam source aligned with neutralizer
- What’s happening to beam after it enters vessel?
  - Plasma-side effects (MHD, 3D fields, etc) ongoing

Neutral Beam troubleshooting

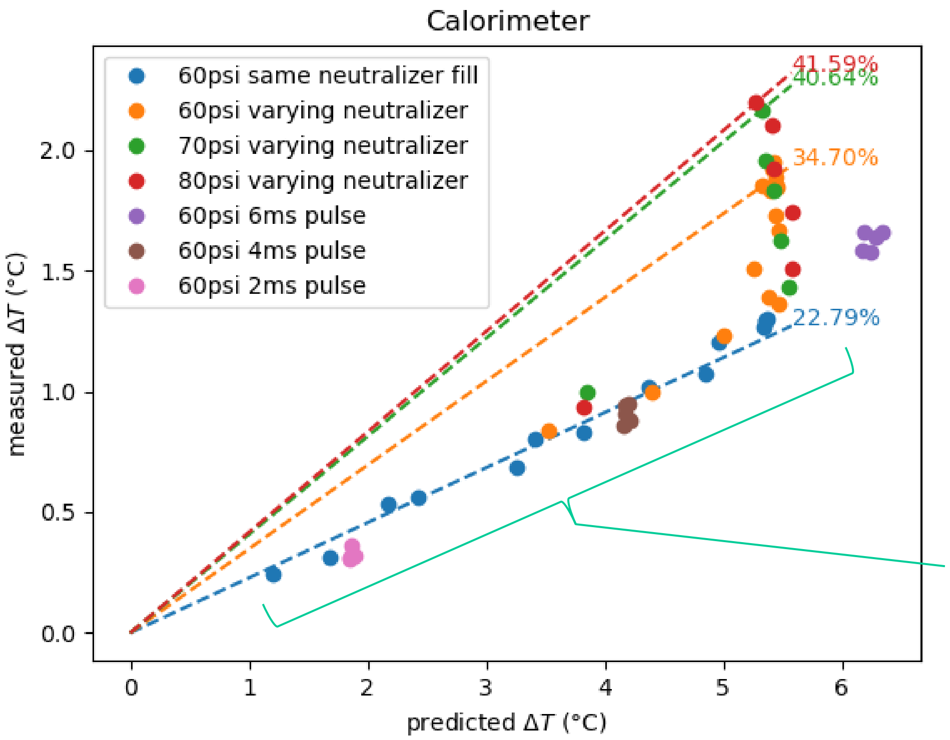


- Fixed thermocouples on calorimeter in beam neutralizer tank
- Bypassed Russian circuitry digitized directly
- New valves
  - More closely recreate original (designed) gas dynamics in source/neutralizer
  - New operational space- needs optimization (ongoing)

Thermocouple data gives multiple paths to improvement

- Temperature traces from thermocouples allowec measure of beam power delivered to calorimete
- Comparison to predicted temperature rise

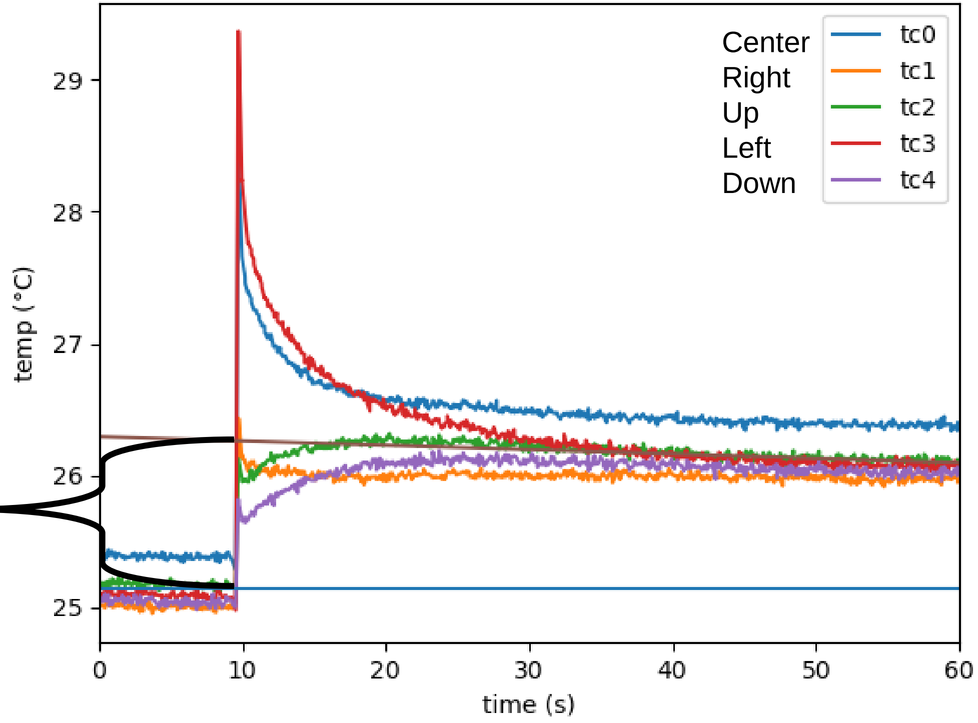
$$\Delta T_{pred} = \frac{\int I_{nbi} E_{nbi} dt}{c_{ps} m_c}$$



Optimizing neutralizer timings/duration/bottle pressure

Default puffing

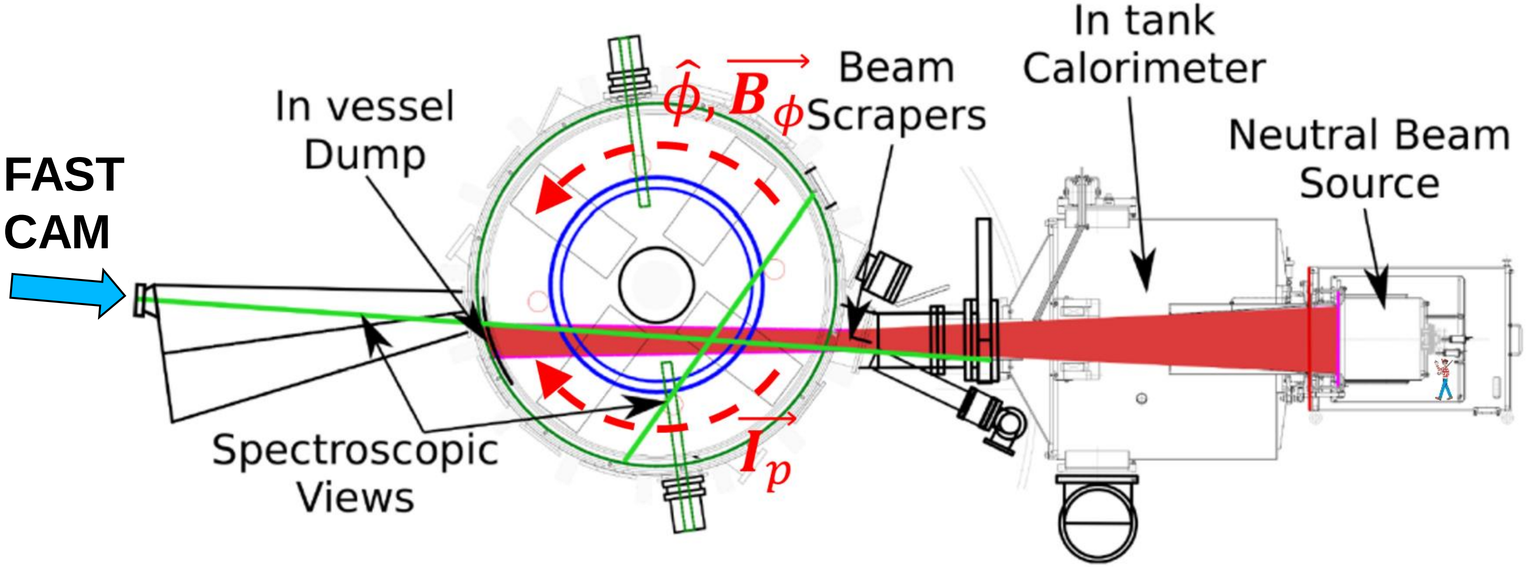
ΔT_{meas}



- This comparison revealed we were **not** equilibrating in neutralizer
- Increased bottle pressure led to quick doubling of power onto calorimeter
- Further improvements have reached ~60% total beam power onto calorimeter

Realignment

- Asymmetry in thermocouples suggests misalignment from source to neutralizer
- Spare source used to help center calorimeter in neutralizer
- Fast camera- good grid usage, no problems, source low (unfixable)



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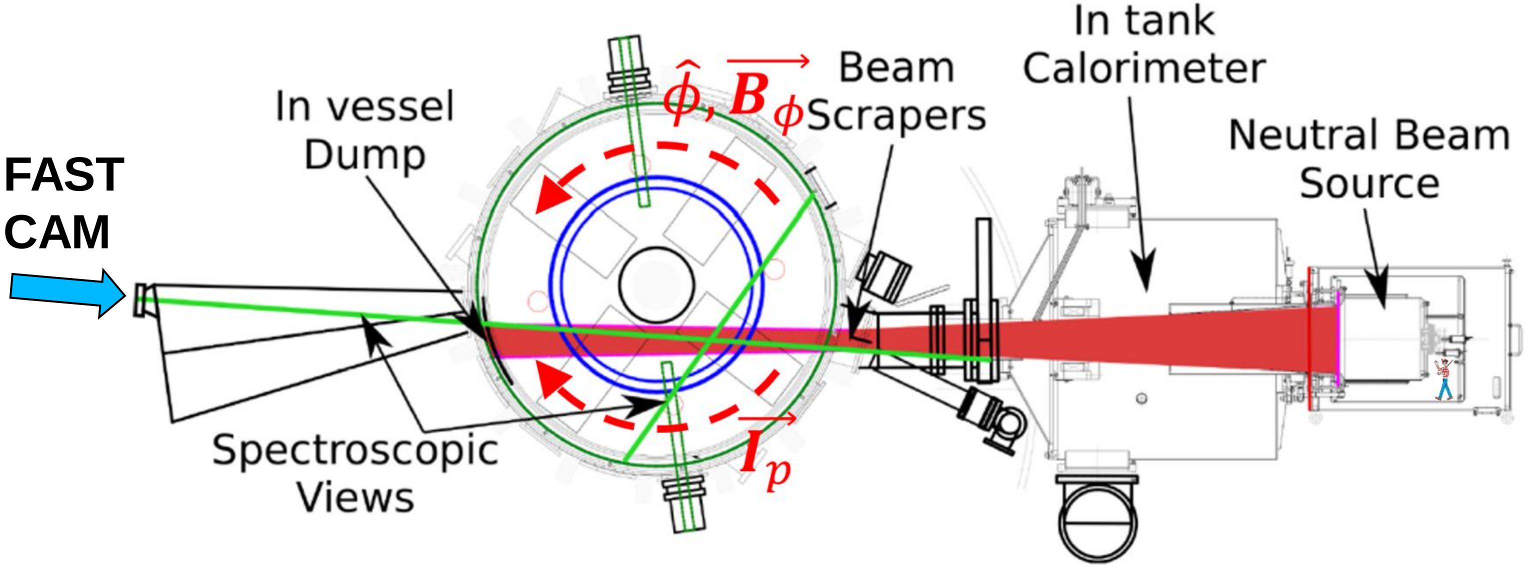
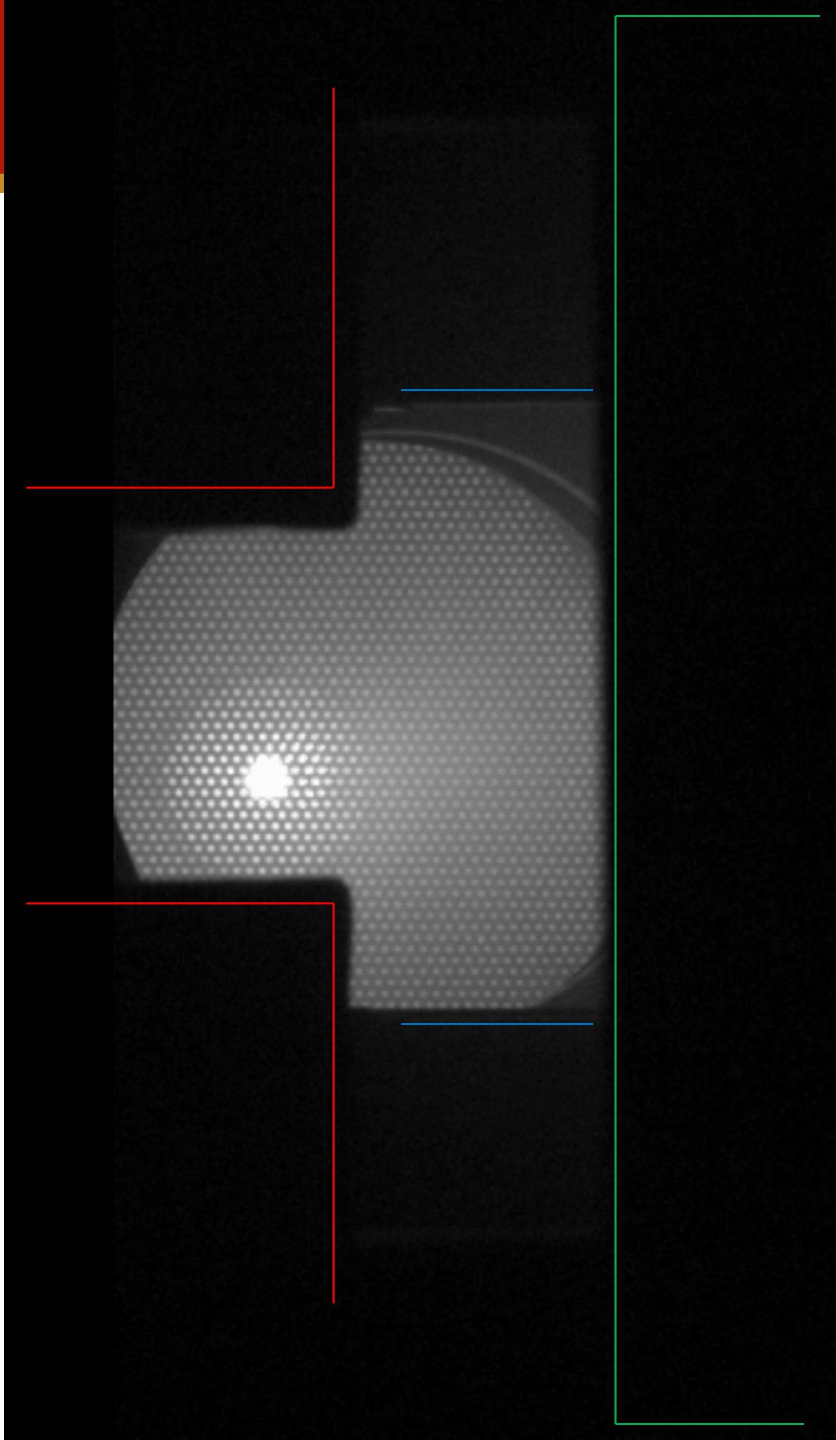
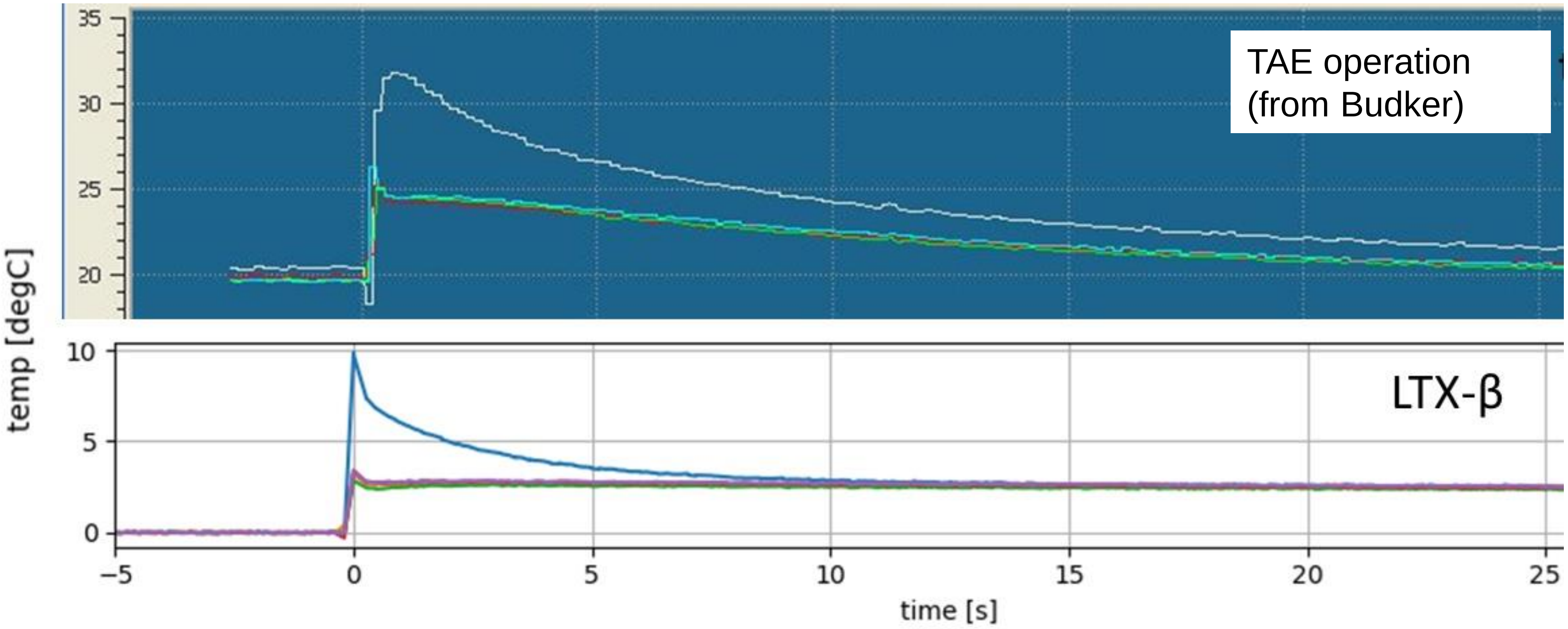




Realignment

- Beam centered on calorimeter
  - Recovered original performance of beam

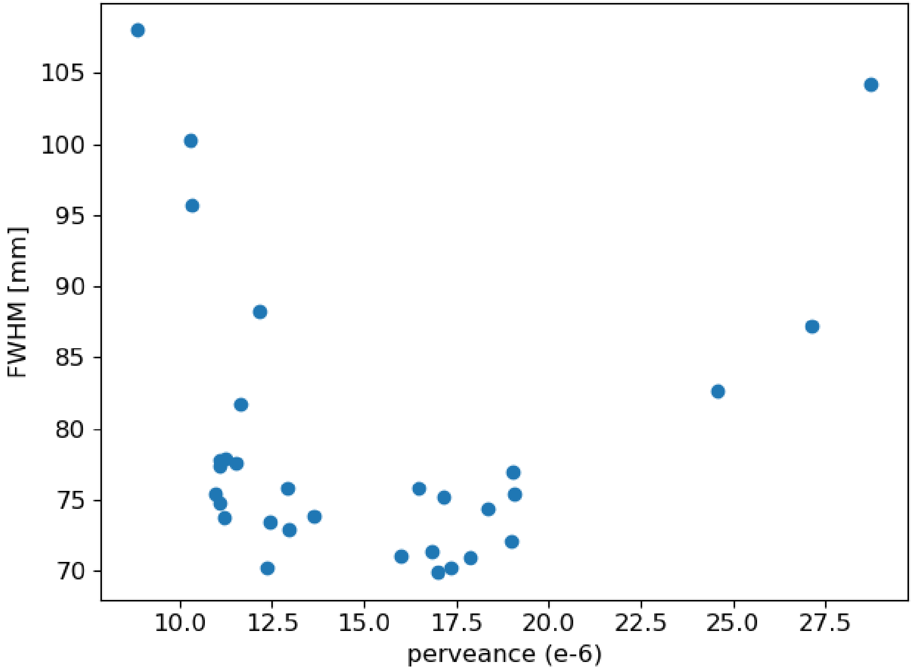


- 20 kV operation at Tri-Alpha
- $\Delta T \approx 12$ ℃

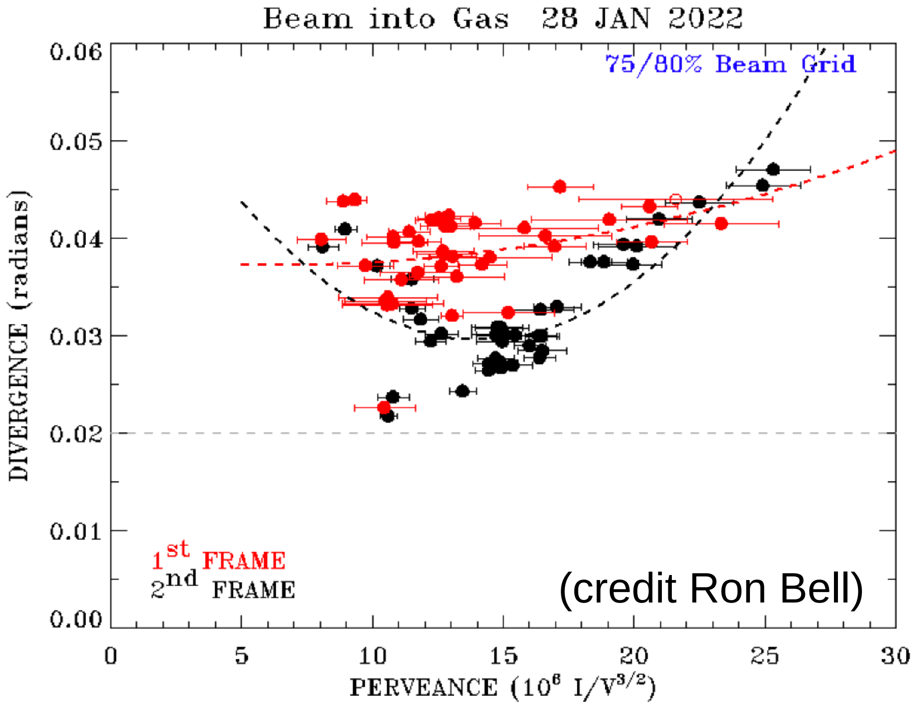
-16 kV LTX operation
- Scales to $\Delta T \approx 12.5$ ℃ at 20 kV

Realignment

- Beam centered on calorimeter
  - Recovered original performance of beam
  - Edge/Core ratio gives beam width estimate- ~7.5cm FWHM at optimal perveance ~ 15e-6



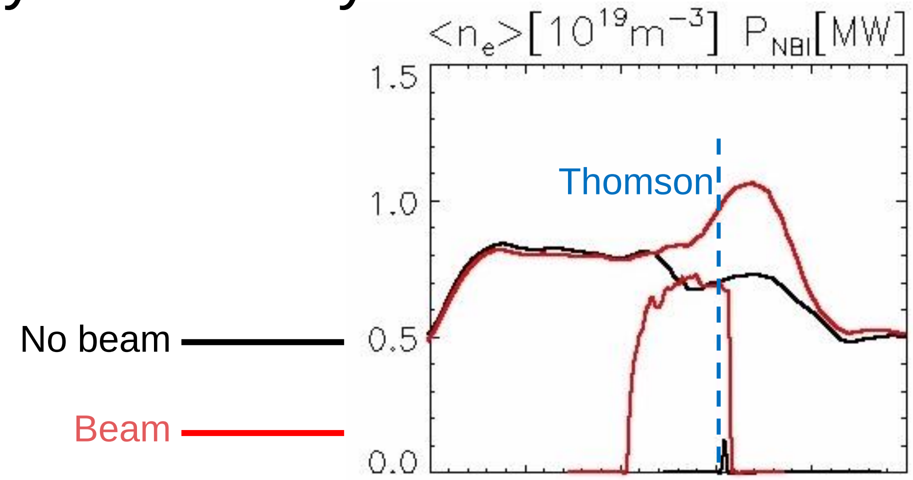
Beam into calorimeter



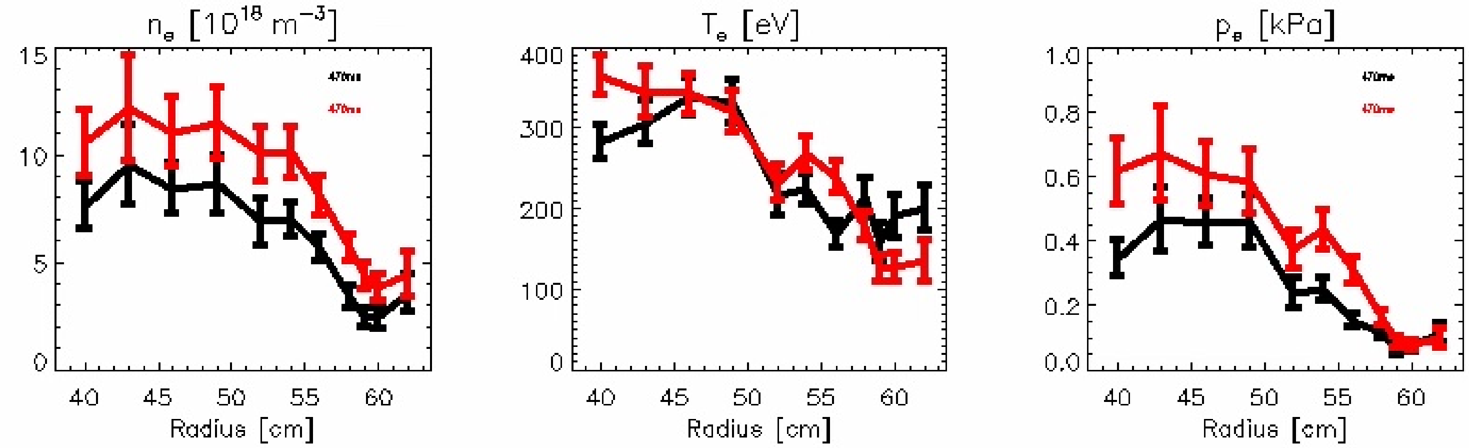
Beam into gas

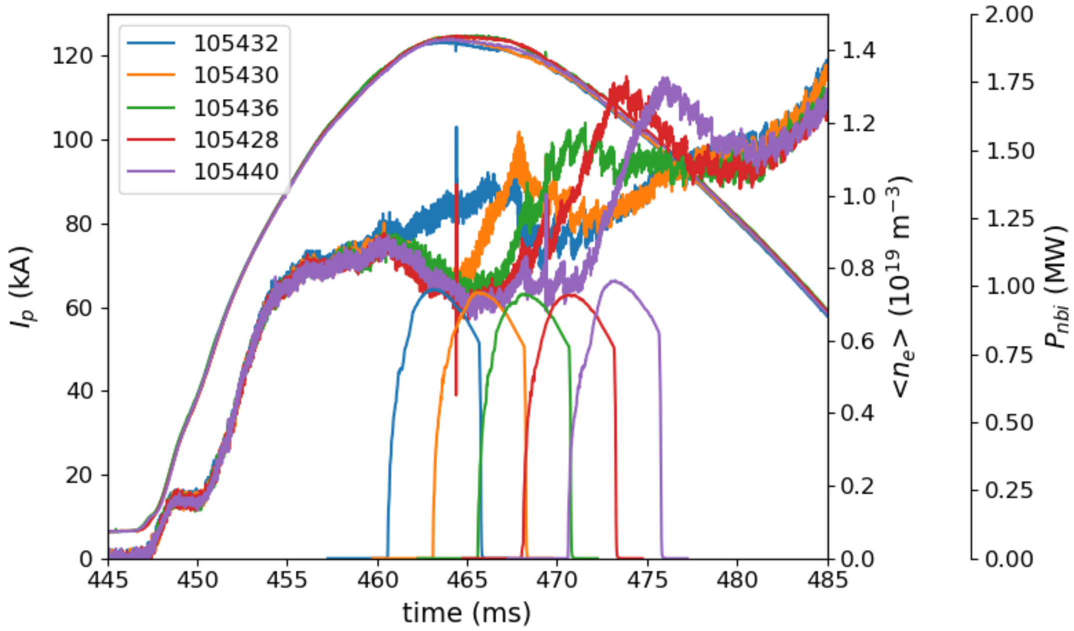
Beam observed in plasma signals(!)

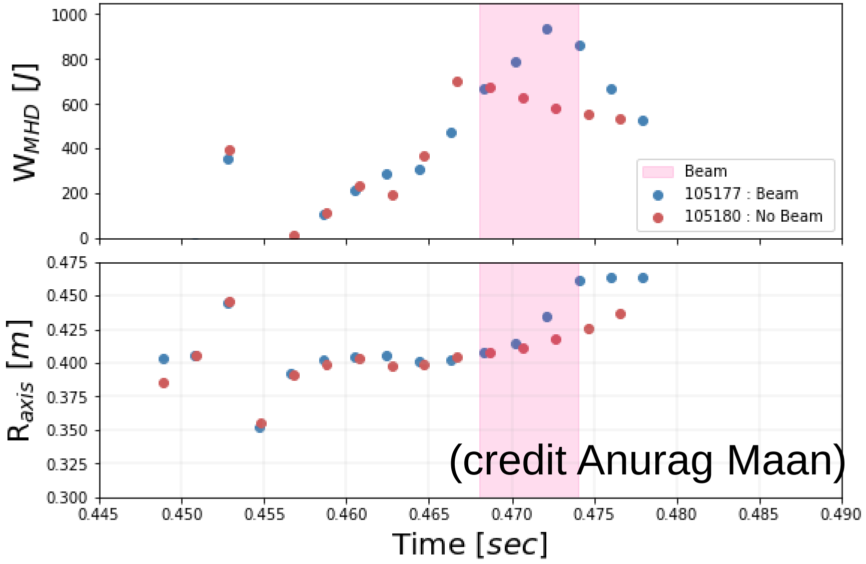
- Significant density rise during beam injection
- ~40% increase in P_e, modest increase in T_e
- Note relatively low density



(credit Dennis Boyle)



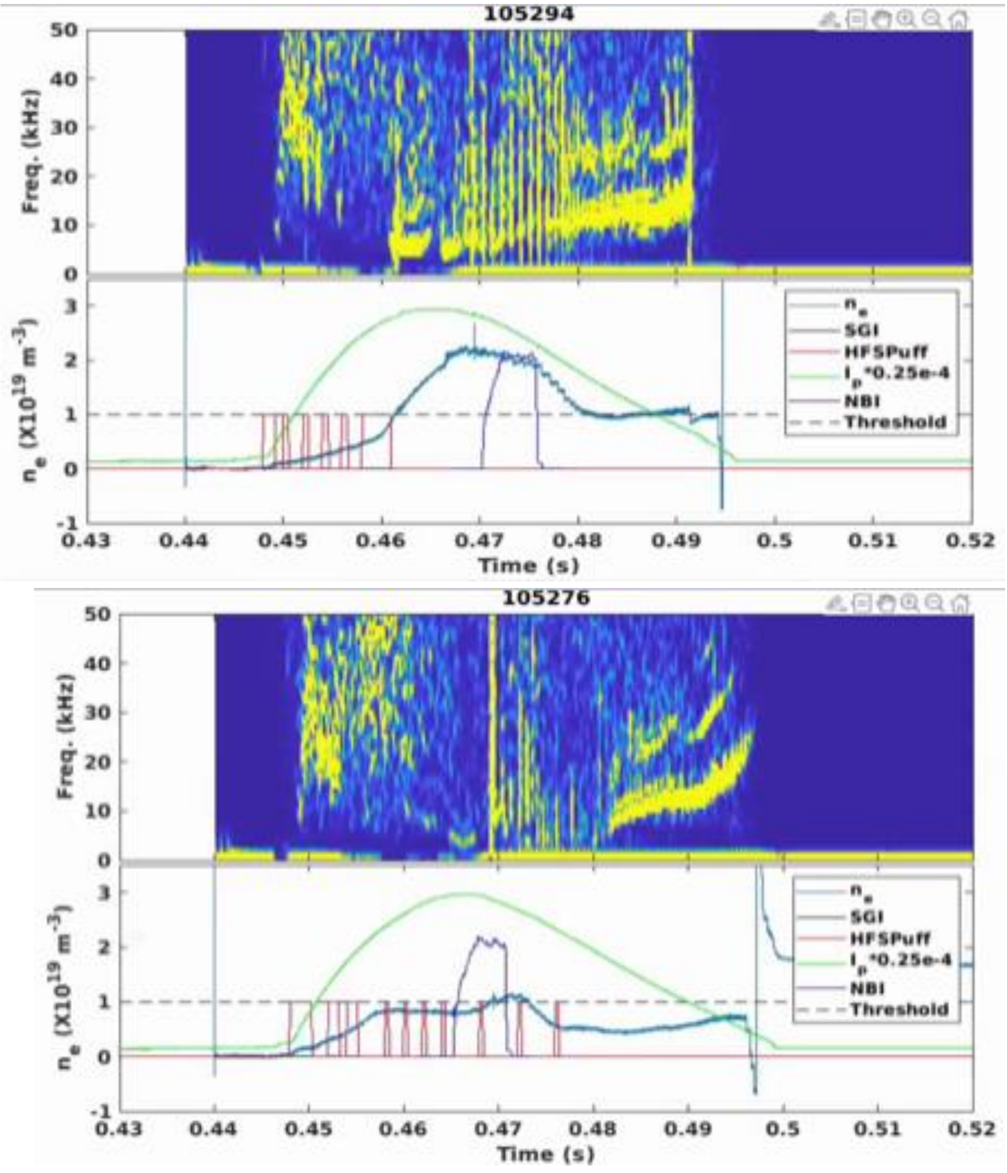




(credit Anurag Maan)

MHD appears related to beam coupling

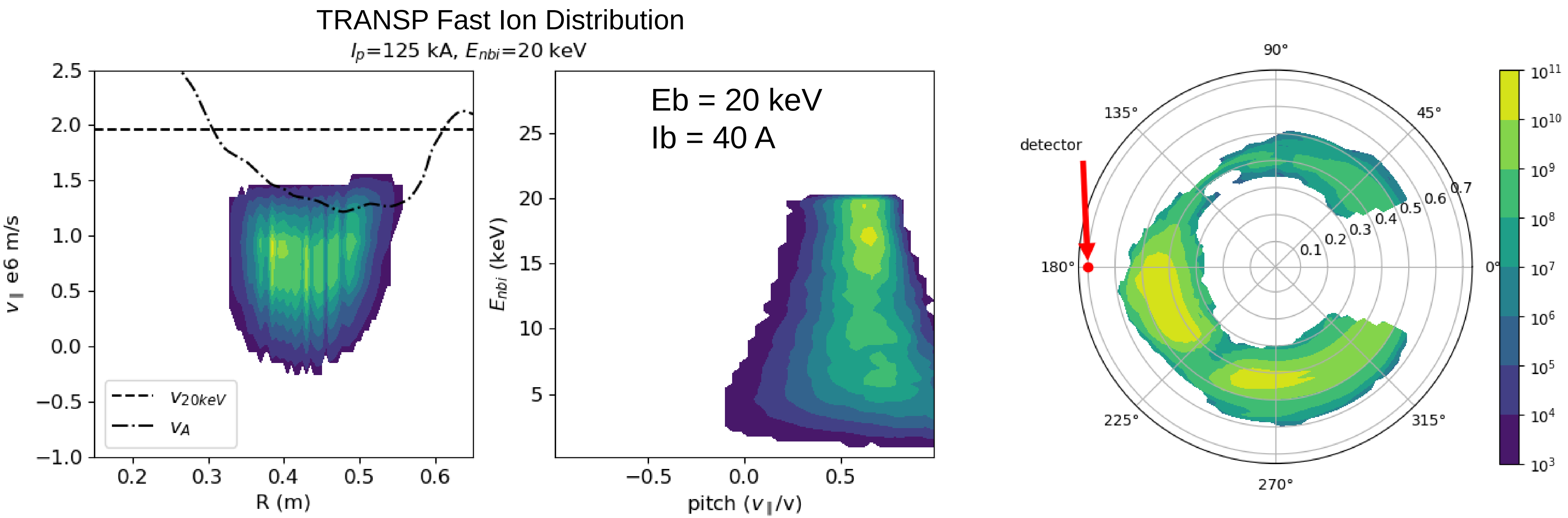
- Tearing mode (2/1) observed for $\langle n_e \rangle > 10^{19} m^{-3}$
- No beam-induced density rise when MHD present
- Initial high plasma current beam injection was high density to encourage beam coupling
- Now investigating relationship between beam and modes
- Note sacrifice running at low density- ~50% shinethrough



(credit Santanu Banerjee)

NPA to diagnose fast ion energy

- TRANSP suggests good confined population
  - Investigate mode interaction!
- Slowing time on order of beam pulse
  - Fully developed near end of pulse, plans to extend beam pulse
- Modeling of NPA (background neutral density) ongoing



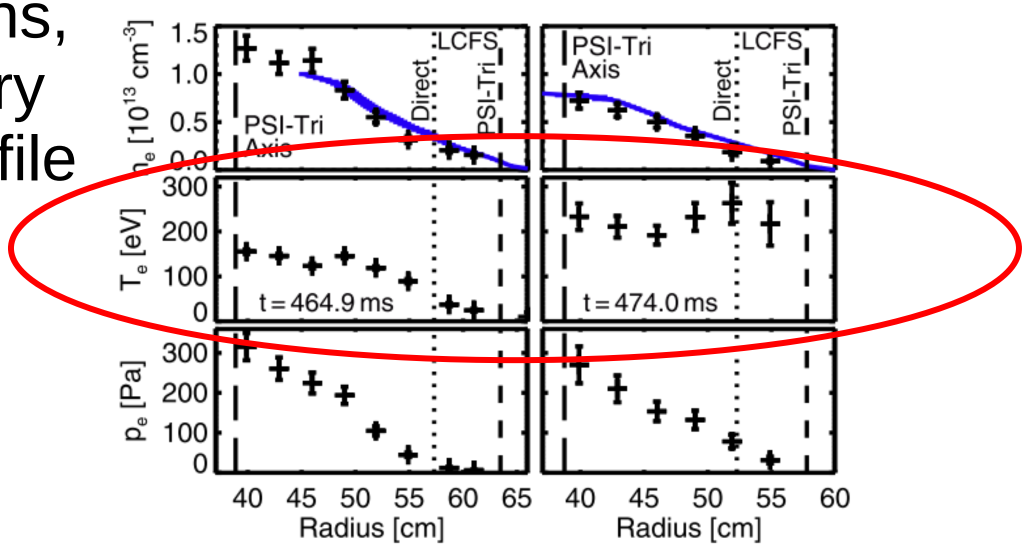
Summary

- Modeling predicted good coupling >100 kA, >1e19m^-3
  - Nothing observed
- Deep dive into beam performance
  - Upgraded beam valves, optimized operation (more work to be done here)
  - Good understanding and confidence in beam behavior
- Preliminary evidence of beam coupling
  - *Lower* density required for coupling (avoid MHD)
  - Much to explore here- beam dependences on mode, orbit characteristics, resonances
- NPA being retrieved for diagnosing fast ion energy spectrum

Thank you!

The low recycling regime in LTX-β

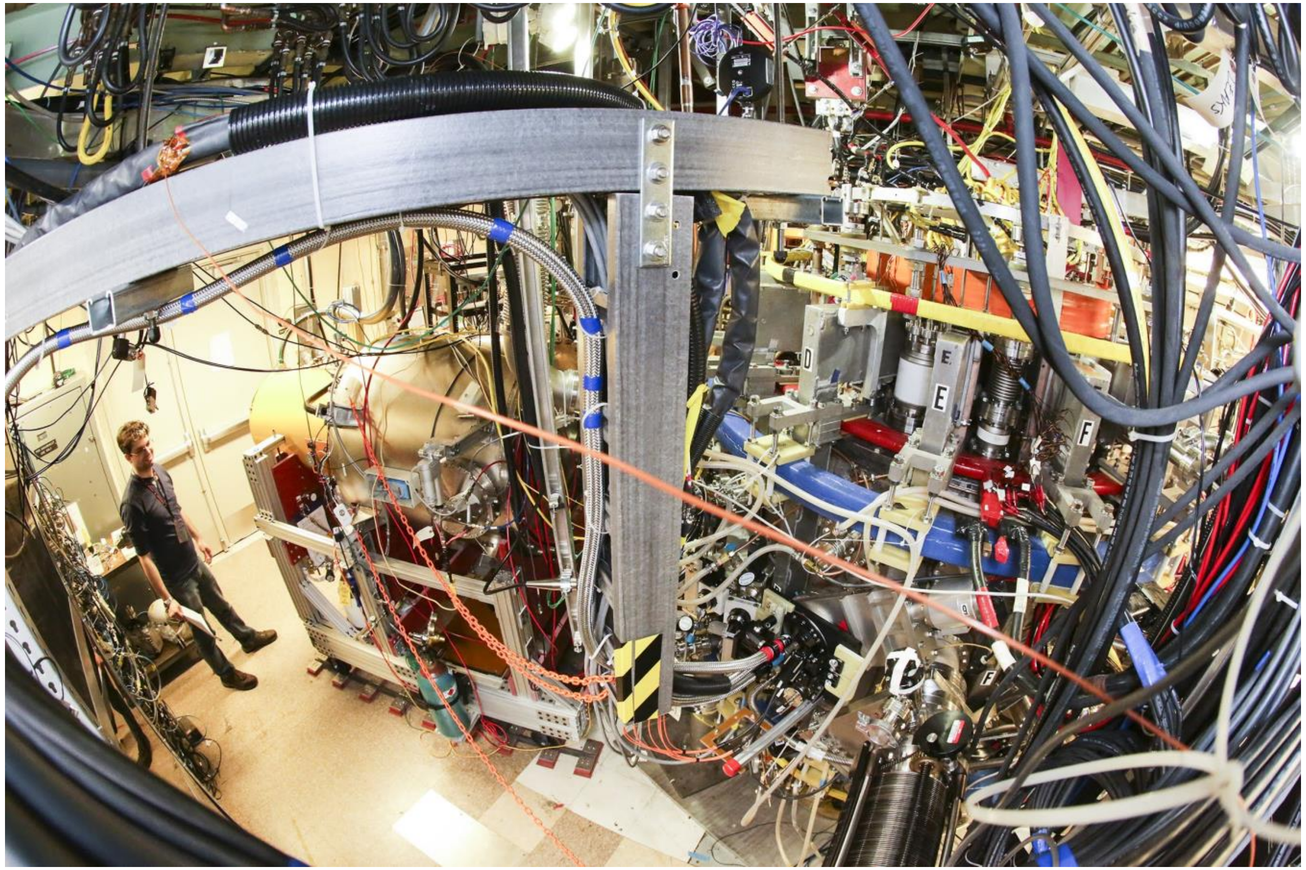
- Atypical of most tokamak plasma conditions, LTX has achieved a low recycling boundary resulting in a flat electron temperature profile [D. Boyle 2017]
- NBI installed 2019: 20keV, 35A
- Good NBI coupling is essential
  - NBI replaces (edge) gas puffing to sustain plasma
  - Study high energy particle dynamics and energy confinement scaling in low R plasmas
  - NBI driven instabilities? Shear stabilization?

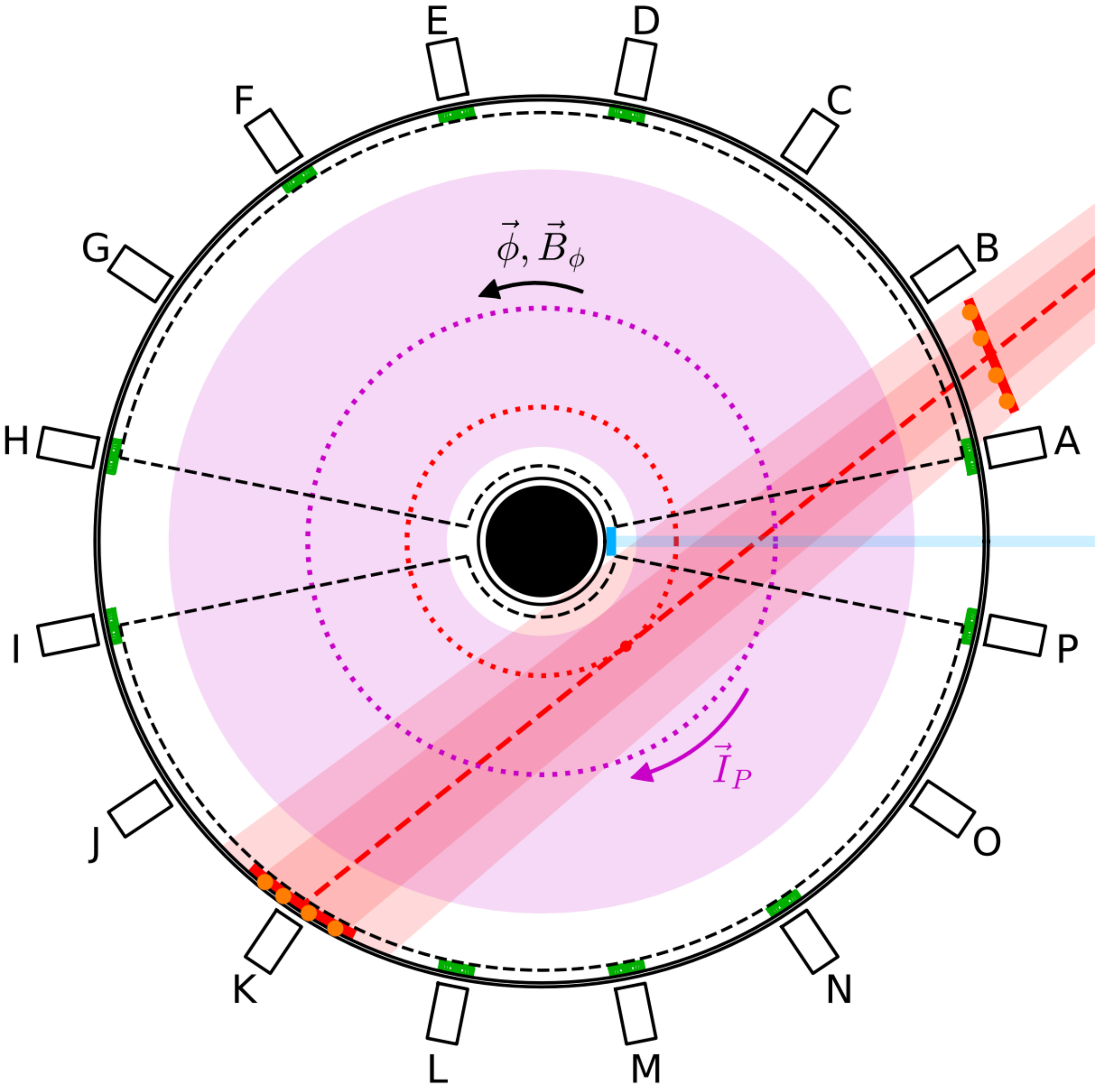


Initial NBI operation revealed near total prompt loss

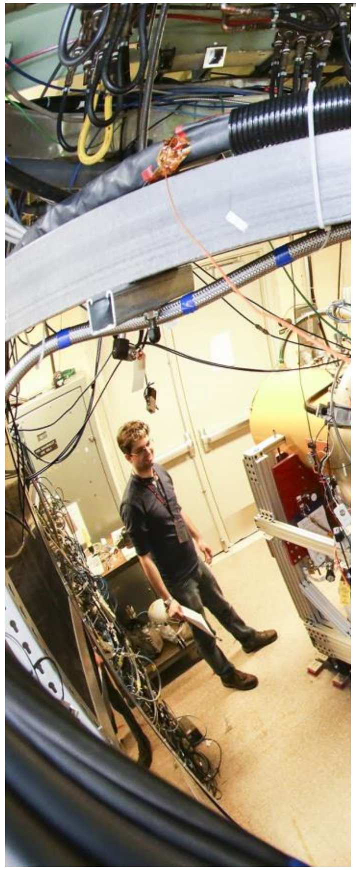
- Ions drift vertically to impact vessel boundary typically within first poloidal transit
- Loss drives counter-NBI torque [Hughes P.E. et al 2021 PPCF (2021)]

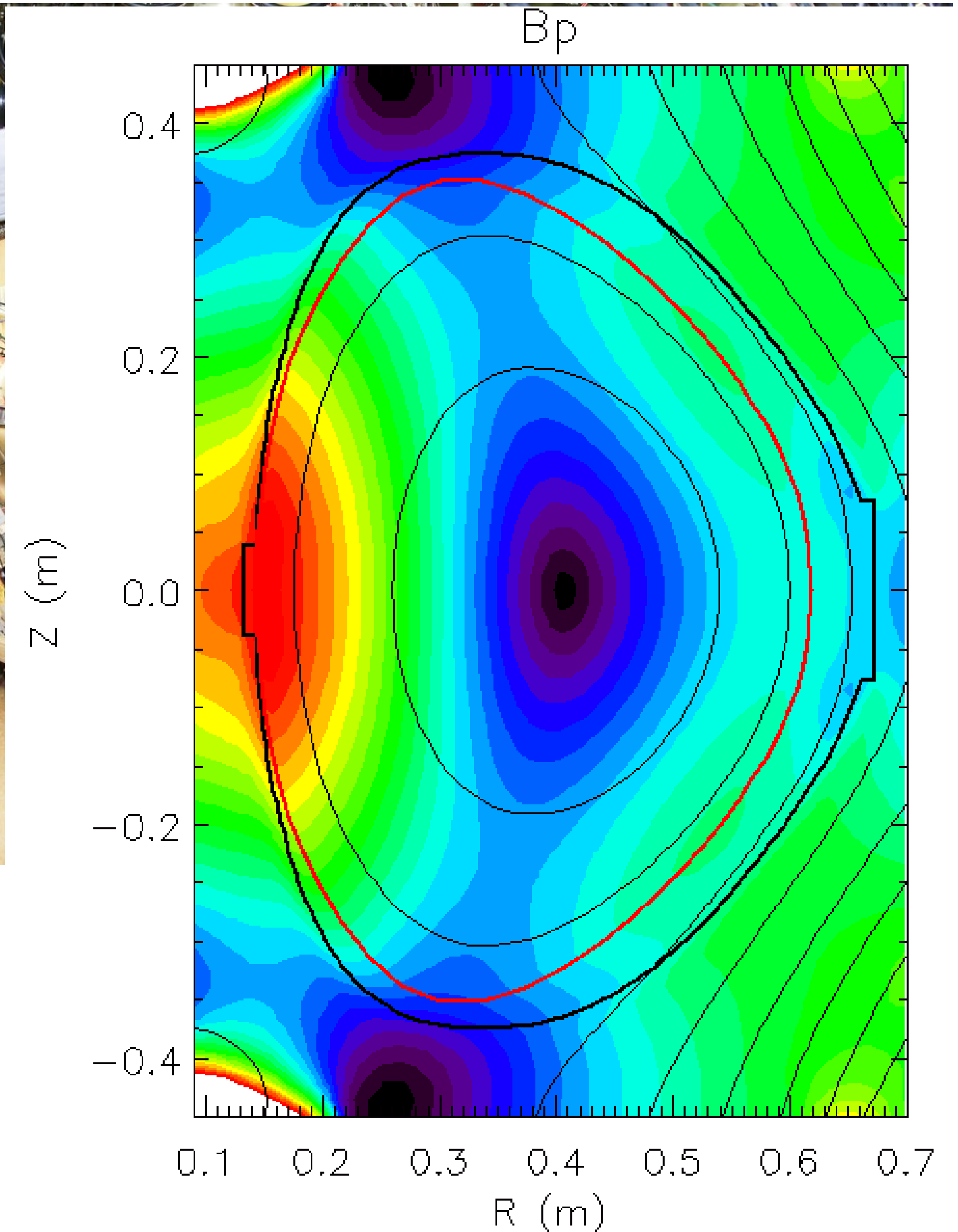
LTX-β



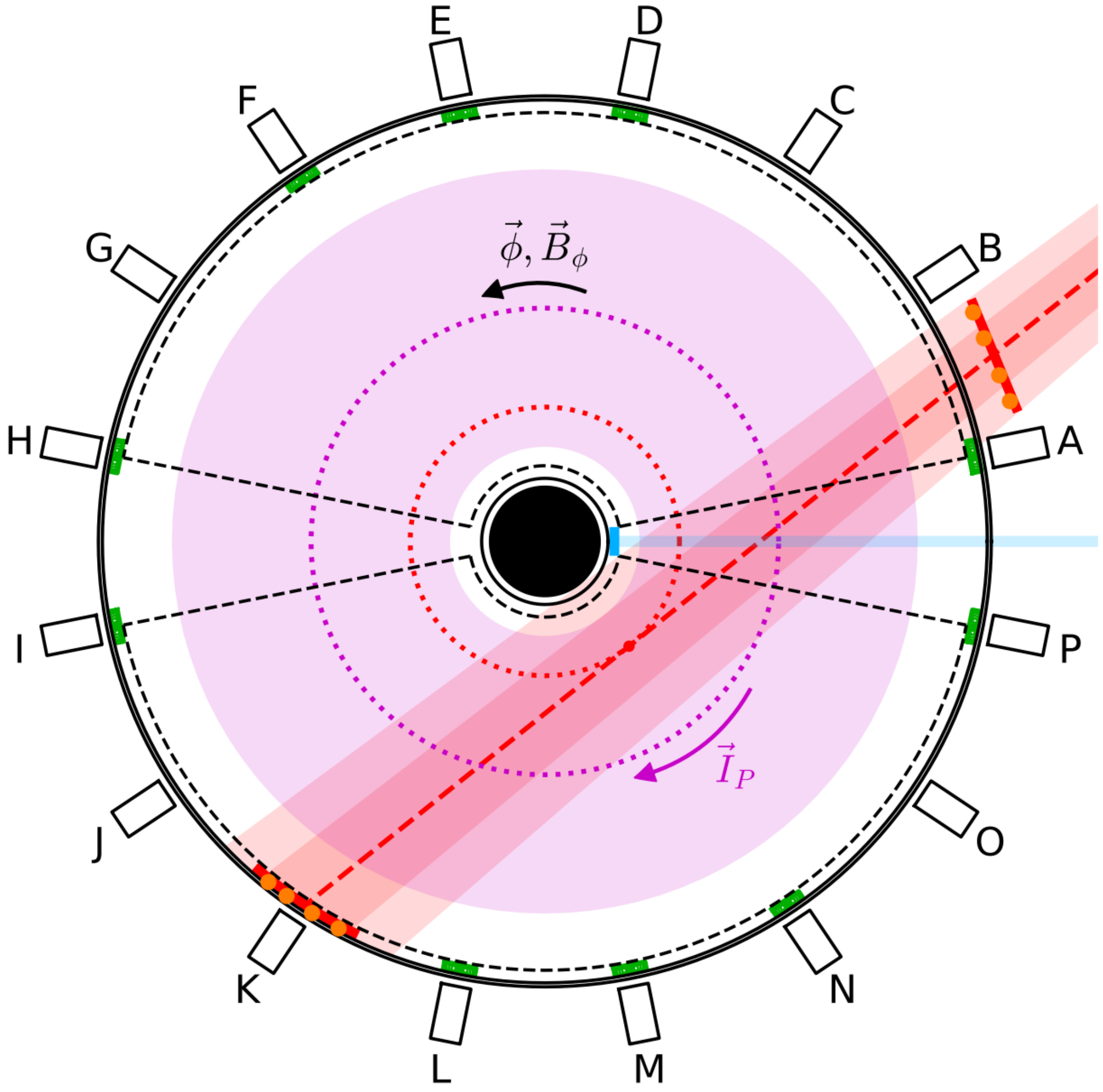


LTX-β





Bp
0.4
0.2
0.0
−0.2
−0.4
Z (m)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
R (m)



A
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Lithium coverage of >90% PFC